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14. ABSTRACT
We have carried out the growth and systematic studies of the optoelectronic and structural properties of AlN epilayers. The results revealed that the threading dislocation (TD) density, in particular the edge TD density, decreases considerably with increasing the epilayer thickness. The screw dislocation density was estimated to be about 5x10^6 cm^-2 in the 4 ?m thick AlN epilaye and is more than one order of magnitude lower than that in GaN of the same thickness. The improved materials were utilized to fabricate deep UV Schottky barrier photodetectors. The fabricated AlN/n-SiC hybrid Schottky barrier detectors exhibited a peak responsivity at 200 nm with very high reverse breakdown voltages and high responsivity and DUV

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Report Title

High Al-content AlGaN alloys for deep UV laser applications

ABSTRACT

We have carried out the growth and systematic studies of the optoelectronic and structural properties of AlN epilayers. The results revealed that the threading dislocation (TD) density, in particular the edge TD density, decreases considerably with increasing the epilayer thickness. The screw dislocation density was estimated to be about 5x10^6 cm^-2 in the 4 ?m thick AlN epilaye and is more than one order of magnitude lower than that in GaN of the same thickness. The improved materials were utilized to fabricate deep UV Schottky barrier photodetectors. The fabricated AlN/n-SiC hybrid Schottky barrier detectors exhibited a peak responsivity at 200 nm with very high reverse breakdown voltages and high responsivity and DUV to UV/visible rejection ratio. Furthermore, we have developed MOCVD growth processes for depositing a-plane AlN epilayers and photonics structures on r-plane sapphire substrates, which will partially address the low efficiency issue of deep UV emitters based on AlGaN. We have also achieved p-type conduction in Al0.7Ga0.3N alloys at elevated temperatures. Although Mg doped AlGaN alloys with high Al contents are generally highly resistive at room temperature, our work has provided a more coherent picture for the conductivity control of AlGaN and AlN.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. T. M. Al Tahtamouni, A. Sedhain, J. Y. Lin, and H. X. Jiang, "Growth and photoluminescence studies of a-plane AlN/AlxGa1?xN quantum wells", Appl. Phys. Lett. 90, 221105 (2007).
2. B. N. Pantha, R. Dahal, M. L. Nakarmi, N. Nepal, J. Li, J. Y. Lin, H. X. Jiang, Q. S. Paduano, and David Weyburne, "Correlation between optoelectronic and structural properties and epilayer thickness of AlN," Appl. Phys. Lett. 90, 241101 (2007).

3. H. X. Jiang and J. Y. Lin, "III-Nitride Micro-Cavity Light-Emitters," – in "Wide Bandgap Light-Emitting Materials and Devices," edited by G.F. Neumark, I. Kuskovsky, and H. X. Jiang, published by Wiley –VCH Verlag GmbH, 2007.

4. R. Dahal, T. M. Al Tahtamouni, J. Y. Lin, and H. X. Jiang, "AlN avalanche photodetectors," Appl. Phys. Lett. 91, 243503 (2007).

5. R. Dahal, T. M. Al Tahtamouni, Z. Y. Fan, J. Y. Lin, and H. X. Jiang, "Hybrid AlN–SiC deep ultraviolet Schottky barrier photodetectors," Appl. Phys. Lett. 90, 263505 (2007).

6. Z. Y. Fan, J. Y. Lin, and H. X. Jiang, "III-nitride micro-emitter arrays: development and applications," Special Issue, J. Phys. D: Appl. Phys. 41 094001 (2008).

Number of Papers published in peer-reviewed journals: 6.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Bed Pantha	0.50
Rajendra Dahal	0.50
FTE Equivalent:	**1.00**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Jing Li	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Hongxing Jiang	0.08	No
Jingyu Lin	0.08	No
FTE Equivalent:	**0.16**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Final Report

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Project Title: High Al-content AlGaN alloys for deep UV laser applications
PI Name: Hongxing Jiang & Jingyu Lin
PI Address: Kansas State University
Period: Oct 1, 2007 to Sep 30, 2008
Program Manager: Dr. John Zavada

I. Summary of Progress

III-nitride wide bandgap semiconductors, with energy band gap varying from 0.9 eV (InN) to 3.4 eV (GaN) to about 6.2 eV (AlN), have been recognized as technologically important materials. Photonic devices based on III-nitrides offer benefits including UV/blue emission; large band offsets of GaN/AlN or InN/AlN heterostructures allowing novel quantum well (QW) device design, and inherently high emission efficiencies. Furthermore, due to their mechanical hardness and larger band gaps, III-nitride based devices may operate at much higher temperatures and voltages/power levels for any dimensional configuration and in harsher environments than other semiconductor devices and are expected to provide much lower temperature sensitivities, which are crucial advantages for many applications. AlGaN alloys with high Al contents, covering from 350 nm to 200 nm, cannot be replaced by any other semiconductor system due to the fact that no other semiconductor possesses such a large direct bandgap (diamond is 5.4 eV with indirect bandgap), as well as the ability of bandgap engineering through the use of alloying and heterostructure design. Efficient ultraviolet (UV) light sources/sensors are crucial in many fields of research. For instance, protein fluorescence is generally excited by UV light; monitoring changes of intrinsic fluorescence in a protein can provide important information on its structural changes.

However, there are many problems and questions that still stand in the way of the practical device implementation of UV photonic devices. Among these, the attainment of highly conductive p-type AlGaN, especially in high Al content AlGaN alloys, remains one of the biggest obstacles for the III-nitride research. Methods for improved material qualities, which would enhance the doping efficiencies and device performance, need to be further explored. The objectives of this ARO research program is to address fundamental material and device issues that are expected to profoundly influence our understanding of the fundamental properties of III-nitrides and their potential applications in new areas beyond UV/visible emitters as well as semiconductor electronics.

We highlight a few examples of our studies below:

- <u>High crystalline quality AlN epilayer growth technology development</u>

We have carried out the growth and systematic studies of the optoelectronic and structural properties of AlN epilayers through the measurements of x-ray diffraction (XRD), photoluminescence (PL) and the dark current of the fabricated AlN DUV photodetectors. The results revealed that the threading dislocation (TD) density, in particular the edge TD density, decreases considerably with increasing the epilayer thickness. The FWHM of XRD rocking curves of the (002) and (102) reflections of a 4 μm epilayer are as small as 63 and 437 arcsec, respectively. These are among the smallest values reported for AlN epilayers and are even smaller than those of the best GaN epilayers grown on sapphire (GaN (002) reflection peak has a FWHM of about 150 arcsec).

From the tilt (out-of plane rotation) and twist (in-plane rotation) spread caused by the mosaicity of the AlN film, the dislocation density was estimated. The screw dislocation density was ~5×10^6 cm^{-2} in the 4 μm thick AlN epilaye and is more than one order of magnitude lower than that in GaN of the same thickness (~10^8 cm^{-2}). This clearly indicates that AlN epilayer is an effective dislocation filter. This reduction in screw dislocation density is particularly important for vertical optoelectronic devices such as LEDs, laser diodes (LDs), and Schottky detectors because screw dislocations are one of the major sources of current leakage paths, which increase with increasing current density. Screw dislocations also behave as non-radiative recombination centers that reduce the output intensity from optical devices.

➢ <u>Hybrid AlN-SiC deep ultraviolet Schottky barrier photodetectors</u>

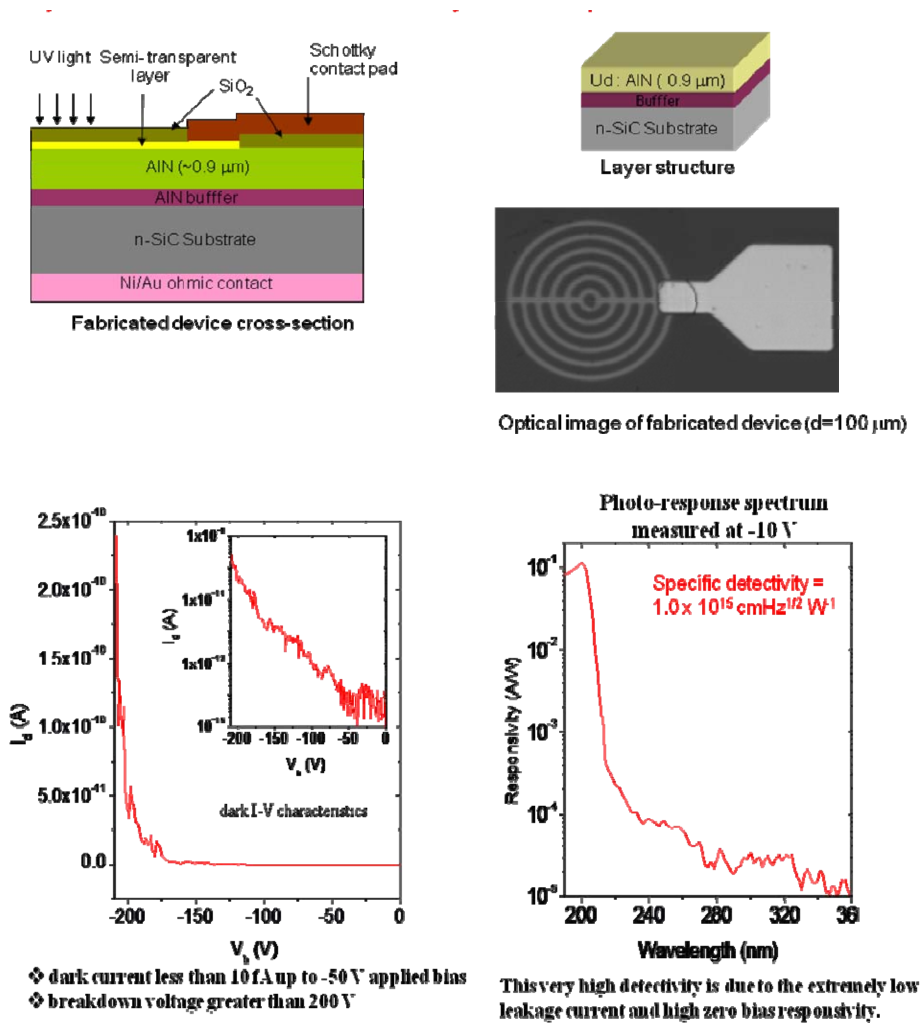

Fig. 1 Hybrid AlN-SiC deep UV Schottky barrier photodetectors

We have successfully fabricated deep UV Schottky barrier photodetectors by exploiting the epitaxial growth of high quality AlN epilayer on n-type SiC substrate (Fig. 1). The fabricated AlN/n-SiC hybrid Schottky barrier detectors exhibited a peak responsivity at 200 nm with very sharp cut off wavelength at 210 nm, very high reverse breakdown voltages (> 200 V), very low dark currents (about 10 fA at a reverse bias of 50 V), and high responsivity and DUV to UV/visible rejection ratio. These outstanding features are direct attributes of the fundamental material properties and high quality of AlN epilayers. The fabricated photodetectors also have a thermal energy limited detectivity at zero bias of about 1.0×10^{15} $cmHz^{1/2}W^{-1}$. These results demonstrated that AlN epilayers are an excellent candidate as an active material for DUV opto-electronic device applications.

➢ <u>Growth of a-plane AlN epilayers and photonics structures on r-plane sapphire substrates</u>

We have also developed MOCVD growth processes for obtaining high quality a-plane AlN epi-templates and a-plane nitride quantum well (QW) structures on r-plane sapphire - an example is shown in Fig. 2 below, which Fig. 2 (a) and (b) show that the emission peak energies of a-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs are all above the band edge transition of the $Al_{0.65}Ga_{0.35}N$ epilayer regardless of the well width (L_w) due to the quantum confinement effect. Conversely, in c-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs, the emission property is dominated by the effects of strong spontaneous and strain-induced piezoelectric fields and the emission peak energy redshifts with L_w and is even below the band edge transition of the $Al_{0.65}Ga_{0.35}N$ epilayer at $L_w > 2$ nm. As illustrated in Fig. 2 (c), c-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs have a narrow range of an optimum choice of QW width ($L_w \approx 2$ nm) in order to obtain highest efficiency, while a-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs show good emission efficiency for all QW width of $L_w > 2$ nm. The results thus demonstrated that a-plane QWs provide a much greater flexibility and larger window for DUV emitter structural design.

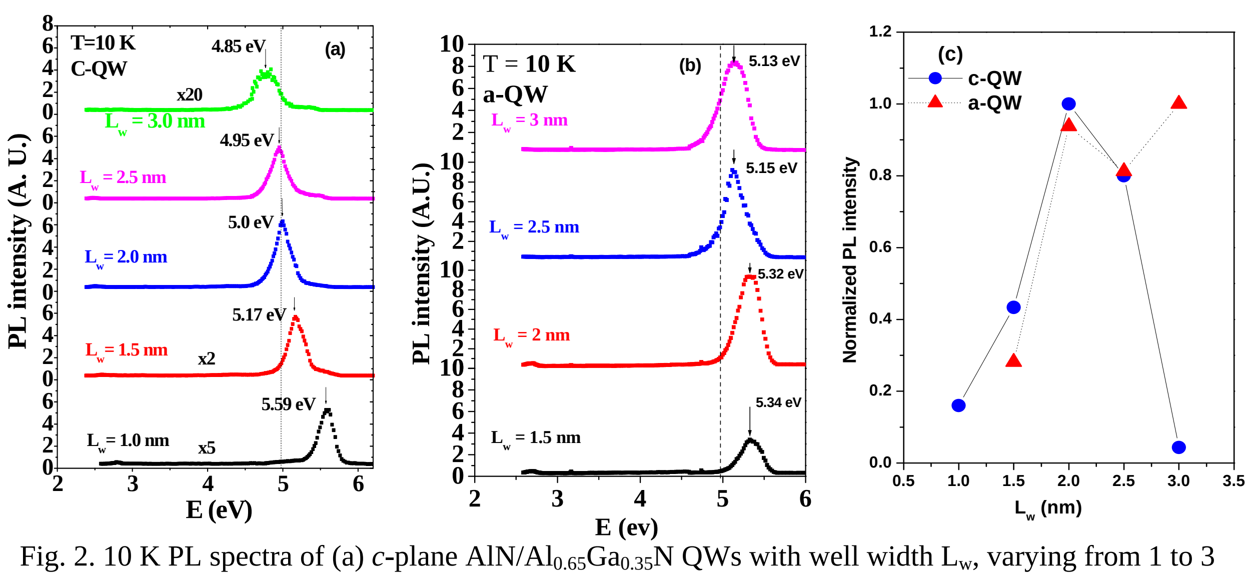

Fig. 2. 10 K PL spectra of (a) *c*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs with well width L_w, varying from 1 to 3 nm (b) *a*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs with well width L_w, varying from 1.5 to 3 nm. All samples have a fixed barrier width of 10 nm. The vertical dashed lines represent the emission peak position of $Al_{0.65}Ga_{0.35}N$ epilayers. (c) Normalized low temperature PL intensity plotted as a function of well width, L_w, for both *a*- and *c*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs.

➢ Fundamental limits of p-type doping in AlN and AlGaN

In Mg doped AlGaN alloys, native defects such as nitrogen vacancies, (V_N^{3+}) and (V_N^{1+}), limit *p*-type conductivity of AlGaN. Figure 3 below compares the 300 K PL spectra of (a) an undoped AlN epilayer, (b) a Mg-doped AlN epilayer with high resistivity, and (c) a Mg-doped AlN epilayer with measureable *p*-type conductivities (or reduced resistivities) at elevated temperatures. Undoped AlN has a strong band-edge emission peak at 5.98 eV due to the recombination of free excitons and exhibits virtually no impurity transitions in the low energy region, ensuring a good optical quality. AFM revealed an atomically smooth surface with a root mean square (RMS) roughness of about 7 Å within a 2 µm x 2 µm scan. These undoped AlN epilayers were employed as templates for the subsequent growth of Mg-doped AlN epilayers. For Mg-doped AlN epilayers, the PL spectra presented in Fig. 3 (b) and 3(c) encompass an emission peak at around 4.7 eV, in addition to the band-edge emission at 5.94 eV. The band-edge emission peak at 5.94 eV has been identified and is due to the recombination of excitons bound to neutral Mg acceptors (or acceptor-bound excitons I_1). We have identified that the 4.7 eV emission line is related to nitrogen vacancies (V_N^{3+}).

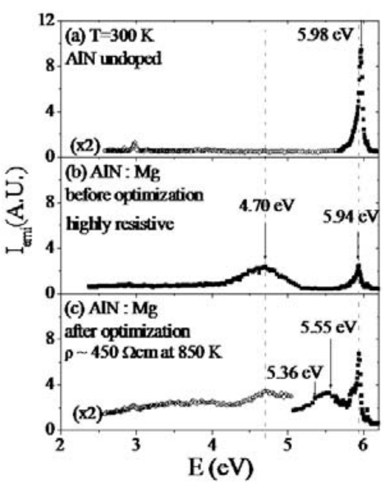

Fig. 3 PL spectra of (a) an undoped and highly resistive AlN epilayer, (b) Mg-doped and high resistive AlN epilayer and (c) Mg-doped AlN epilayer with measureable p-conductivity at T > 600 K.

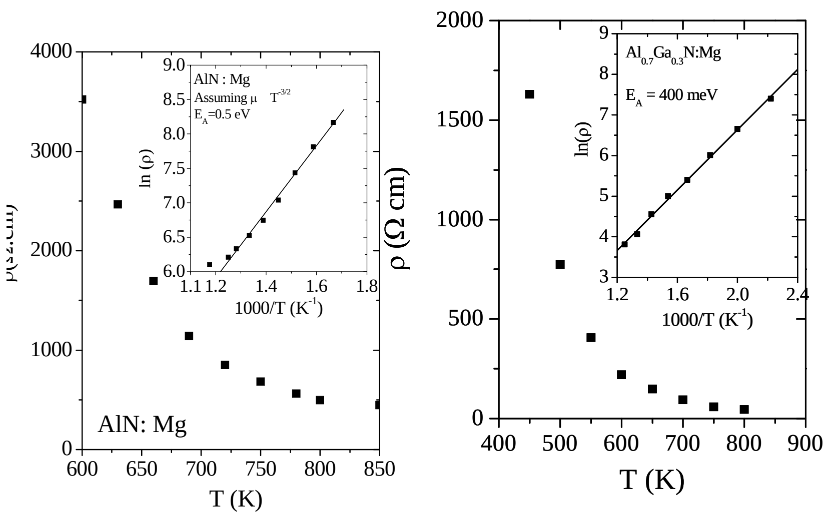

Fig. 4. Temperature dependent resistivity of an Mg-doped AlN epilayer (Left) and $Al_{0.7}Ga_{0.3}N$ epilayer (Right). Insets: Estimated activation energy, E_A, of Mg acceptor is ~ 0.5 eV in AlN and is ~ 0.4 eV in $Al_{0.7}Ga_{0.3}N$. Optimized Mg-doped $Al_{0.7}Ga_{0.3}N$ and AlN epilayers have measureable p-conductivity at T > 400 K and T > 600 K, respectively.

A clear correlation between the electrical and optical properties of Mg-doped AlN epilayers has been observed. Samples exhibiting strong emissions at 4.7 eV, such as that shown in Fig. 3(b), are generally highly insulating. Hall-effect measurements were carried out at elevated temperatures. The resistivity for one of our Mg-doped AlN epilayers, in which the intensity of nitrogen vacancy (V_N^{3+}) related emission line at 4.7 eV was minimized, was measured in the temperature range between 400 and 900 K and the result is shown in Fig. 4 (Left), from which an activation energy of about 0.5 eV for Mg acceptor in AlN was obtained. This represents the first electrical measurement result for Mg acceptor activation energy in AlN.

Furthermore, by monitoring the V_N^{3+} related PL emission to the band edge emission intensity and p-type resistivity at elevated temperatures, we have confirmed p-type conduction in

$Al_{0.7}Ga_{0.3}N$ alloys at elevated temperatures and a p-type resistivity of about 40 Ω-cm at 800 K was observed, as illustrated in Fig. 4 (Right). Although Mg doped AlGaN alloys with high Al contents are generally highly resistive at room temperature, our work has provided a more coherent picture for the conductivity control of AlGaN and AlN and determined the Mg acceptor energy level in AlGaN of the entire alloy range.

II. Publications resulted from ARO support:

1. T. M. Al Tahtamouni, A. Sedhain, J. Y. Lin, and H. X. Jiang, "Growth and photoluminescence studies of *a*-plane AlN/$Al_xGa_{1-x}N$ quantum wells", Appl. Phys. Lett. 90, 221105 (2007).
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